

Design and Control of a Multi-Port DC–DC Converter for Integrated Solar PV, Fuel Cell and Battery

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Abstract – *This paper presents the design and simulation of a multi-port DC-DC converter that integrates a solar photovoltaic (PV) array, a fuel cell and a battery energy storage system in a single power-conversion stage. The possibility to integrate all three sources in a single converter decreases the number of components, conduction losses and the overall system complexity in comparison to a converter dedicated to each source. The Perturb and Observe (P&O) algorithm is used to track the maximum power point of the PV array and a Proportional-Integral (PI) controller is used to keep constant the DC-link voltage and to coordinate the power sharing among the sources. The battery is cycled, charging and discharging, to maintain supply even when the PV or fuel-cell output fluctuates. The whole system has been designed and simulated in MATLAB/Simulink under different operating conditions. The obtained results show a stable DC-link voltage, a high voltage gain and a smooth power sharing between the sources. The converter is therefore well suited for hybrid renewable energy applications such as DC microgrids, stand-alone power systems and electric vehicle charging stations.*

Keywords— *Multi Port DC DC Converter, Solar PV, Fuel Cell, Battery Energy Storage System, MPPT, PI Controller.*

I.INTRODUCTION

Growing concerns over energy security and environmental sustainability have pushed hybrid renewable energy systems to the forefront of modern power system design. Solar photovoltaic (PV) generation is particularly attractive due to its wide availability, low running cost and low environmental footprint. However, the output of solar PV is intrinsically intermittent as it rises and falls with the irradiance and temperature. Therefore a system based purely on PV cannot be relied upon to supply power continuously. One of the more practical ways to close this gap and keep the supply stable is to combine PV generation with a fuel cell and a battery energy storage unit[1], [2]. Hybrid systems are well suited to multiport DC-DC converters as a single conversion stage can accept power from multiple sources simultaneously. This topology needs lesser number of switching devices, lesser switching losses, lesser space and better power density and conversion efficiency, when compared to the case of using a separate converter for each source [3], [4]. This also simplifies the overall control problem, since the power flow among the sources can be coordinated from one place itself. In these hybrid systems, usually the PV array provides power during normal operation, the fuel cell is activated when solar generation is not enough, and the battery is charged and discharged to smooth out transient mismatches, maintain the DC-link voltage and add an extra layer of reliability to the system [5], [6], and the load is supplied uninterruptedly irrespective of the variations in conditions due to proper coordination of

these three sources. Maximum Power Point Tracking (MPPT) in some form is necessary to operate a PV array at its maximum power point with changing irradiance and temperature. The Perturb and Observe (P&O) method is still the most popular MPPT technique because of its simplicity, fast convergence and good tracking ability [7], [8]. The Proportional-Integral (PI) controller is usually used to control the DC-link voltage to its reference value and to reach an acceptable power sharing ratio between the PV array, fuel cell and battery. In literature many hybrid converter topologies have been proposed but most of them still suffer from high component count, switching stress or limited voltage gain [9], [10], these disadvantages increase cost and decrease the efficiency, effect which is more evident in medium and high power renewable energy applications. What is still missing is a converter that is small, high voltage gain and efficiently deals with multiple sources without increasing control complexity. The paper proposes a high-gain multiport DC-DC converter that integrates a solar PV array, a fuel cell, and a battery energy storage system into a single conversion stage to fulfill this need. The simplicity of the topology is maintained with a high voltage gain and coordinated power management. A P&O algorithm is used to maximize the PV output while a PI controller is used to regulate the voltage of the DC-link and to control the power flow between the three sources. The entire system was modeled and validated in MATLAB/Simulink under various operating conditions. The results show the effectiveness of power sharing, stable DC-link voltage, high voltage gain and reliable performance, which makes the converter suitable for DC microgrids, standalone renewable energy systems, and electric vehicle charging applications.

II.SYSTEM DESCRIPTION

The proposed hybrid renewable energy system consists of solar photovoltaic (PV) array, fuel cell (FC), battery energy storage system (BESS), high gain multi-port DC-DC converter (MPDC), PI controller, MPPT controller and DC or AC load. This means that all three sources undergo a single conversion stage and hence there are fewer individual converters, lower switching loss, smaller converter footprint and less overall system complexity. This improves the power density, increases the conversion efficiency and simplifies the energy management across the available sources. Under normal conditions, the PV array is the primary source of power and the fuel cell is the backup source when solar irradiance is low or PV generation is inadequate. The battery is charged in bidirectional mode, absorbing excess energy during charging and releasing it in periods of high load or low renewable generation, ensuring uninterrupted power delivery and enhancing overall system reliability. The control strategy is based on the combination of a Perturb and Observe (P&O) Maximum Power Point Tracking (MPPT) algorithm and a Proportional-Integral (PI) controller: the MPPT phase is used to track the maximum power point of the PV array during the irradiance and temperature variations, while the PI controller controls the DC-link voltage and modifies the duty cycle of the converter so that it can share the power among the PV array, fuel cell and battery. The two controllers are combined to generate a stable output voltage, fast dynamic response, less voltage ripple, and better performance. The complete hybrid system was modeled and validated in MATLAB / Simulink under different operating conditions to assess its steady-state and dynamic behavior.

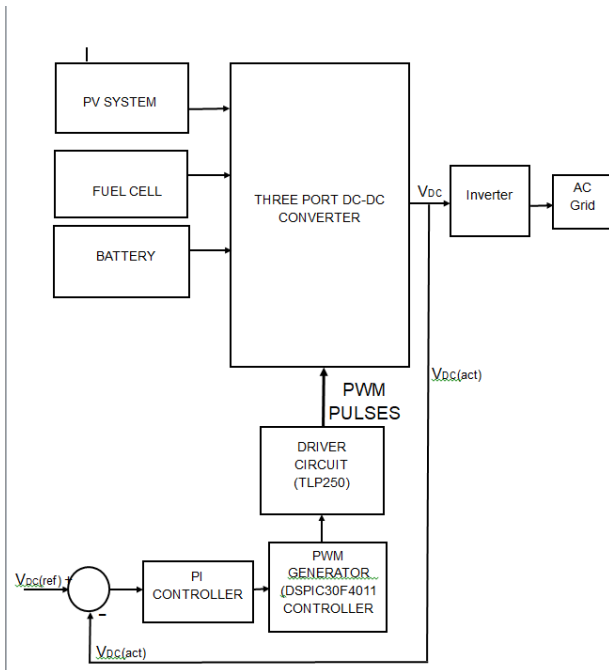


Fig.1. Proposed Multiport dc to dc converter System

A. Solar Photovoltaic(PV)Array

The primary renewable energy source in this hybrid system is the photovoltaic (PV) array which directly converts the solar irradiance into electrical energy by the photovoltaic effect. In an effort to keep the power extraction closer to its maximum under changing environmental conditions, a Perturb and Observe (P&O) Maximum Power Point Tracking (MPPT) algorithm is used, as its output voltage and current varies with irradiance and ambient temperature. The extracted power is then passed to the multi-port DC-DC converter for further processing

B. Fuel Cell (FC)

The fuel cell represents an auxiliary source which makes the hybrid system more reliable and continuous. This auxiliary source is used whenever the PV output is insufficient because of low irradiance or sudden load changes. It has a steady DC output, which helps to maintain the load during transients, thus increasing the

overall system efficiency and avoiding interruptions in the power supply.

C. Battery Energy Storage System (BESS)

The battery energy storage system functions as an energy buffer, holding surplus energy from the PV array during high-irradiance periods and releasing the stored energy when renewable generation is low or load demand increases. It works in bidirectional mode, charging and discharging as necessary to optimize the overall power balance, increase system stability and help keep the DC-link voltage constant.

D. Multi- Port DC–DC Converter

The principal power processing element of the system is a high gain multi-port DC-DC converter that interfaces the PV array, fuel cell and batteries using one conversion stage. It offers high voltage gain with low switching losses, less components and low conversion losses. This design allows the power to flow efficiently between the numerous sources while keeping the output voltage steady under various operating situations.

E. Perturb and Observe (P&O) MPPT Algorithm

The Perturb and Observe (P&O) MPPT algorithm continuously perturbs the PV array operating voltage and observes the change in the power to track the maximum power point. It estimates the optimum operating point from the observed data. Then the converter duty cycle is tuned to obtain the maximum power from the PV system. The P&O algorithm is easy to implement and reasonably fast, and tracks well with changing solar irradiance.

F. PI Controller

A Proportional–Integral (PI) controller regulates the converter's DC-link output voltage: it continuously compares the measured output against a reference value to produce an error signal, and uses that error to generate the control signal that drives the PWM generator and, in turn, the converter's switching pulses. This keeps steady-state error low, sharpens the dynamic response, and keeps power sharing balanced among the photovoltaic array, fuel cell, and battery.

H-Bridge Voltage Source Inverter

An H-Bridge Voltage Source Inverter (VSI) is a power electronic converter that converts a set DC voltage into an AC voltage. It uses four power semiconductor switches such as MOSFETs or IGBTs, configured in the shape of the letter "H". The inverter receives its power from a DC source (battery, photovoltaic (PV) system, fuel cell or DC bus) and the load is connected across the bridge's two legs. Alternately closing diagonal pairs of switches reverses the polarity of the voltage across the load, resulting in an alternating voltage. If switches S1 and S4 are turned ON, the load gets a positive voltage (+V_{dc}), and when switches S2 and S3 are turned ON, the load gets a negative voltage (–V_{dc}). The switches in the same leg can never be turned ON simultaneously, else a short circuit across the DC source will occur. A tiny dead period is introduced between the switching transitions.

G. Overall System Operation

In normal operation, the PV array is the main source feeding the load and the P&O MPPT algorithm maintains it at its maximum power point. The battery charges and discharges to smooth out transient variations as required. Where solar power is insufficient the fuel cell fills the gap. The multi-port converter connects all the three sources and gives a

regulated DC output. The duty cycle is regulated by the PI controller to maintain the DC-link voltage at a constant level as the sources and loads vary. The PV array, fuel cell, battery, MPPT algorithm, and PI controller together ensure efficient power management, minimize voltage fluctuations, and provide an overall responsive and reliable system.

III.PROPOSED SYSTEM DESIGN

The design incorporates multiple renewable sources using a multi-port DC–DC converter to provide reliable and uninterrupted power supply. It comprises of a solar PV system, fuel cell, battery energy storage system, multi-port converter, controller and H-bridge voltage source inverter, integrated for efficient power management and voltage regulation. Solar PV system is the main source of power generation, which converts irradiance to DC power. As this power supply is intermittent, a fuel cell is used to back it up when solar generation is not enough, and a battery is used to store excess energy so that it can be used in sudden load swings or low-generation periods. The three sources are connected to the multi-port converter which deals with the power flow between them. The primary purpose of the converter is to step up and regulate the voltage from these different sources and to change modes based on the availability of the sources. The converter will supply the load and top off the battery when the solar power is sufficient, and depend on the fuel cell and battery when the solar power is low. The bidirectional flow is maintained so that the battery may charge and discharge as needed. A PI controller is used to regulate the DC-link voltage by comparing the output with a reference value and converting the resulting error into control signals. These control signals are then converted into PWM pulses which drive the switching devices in both the converter and the inverter. The regulated DC output is then given to H- Bridge Voltage Source Inverter which converts it to AC for AC loads. There is a filter in the output to cut harmonics and clean up the waveform. In the real design, the solar PV source (60 V) is the primary source in daytime, the fuel cell (48 V)

is the secondary source when the solar power is not enough, and the battery (48 V) is the storage that helps to maintain the output voltage in transients. These three sources are then combined in a multi-port boost converter that steps the energy up to the desired 600 V DC output. The boost converter consists of inductors, capacitors, power switches and diodes. The inductor stores energy and smooths the current ripple while the capacitor filters the voltage ripple and stabilizes the output.

The switching devices control the flow of energy from each source and are responsible for sharing the power efficiently between the PV array, the battery and the fuel cell.

The system can work in different modes depending on the availability of the source:

- PV Mode – Load supplied by solar panel and battery charged
- Hybrid Mode – PV and fuel cell supply load together
- Battery Mode – Battery supplies load when generation is low
- Full Hybrid Mode – PV + Fuel Cell + Battery power load simultaneously

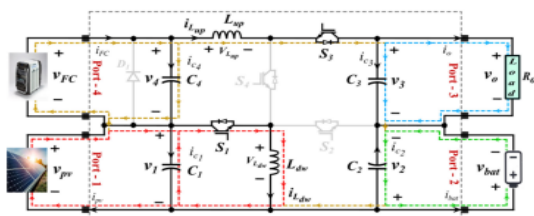


Fig.1. Proposed Multiport System

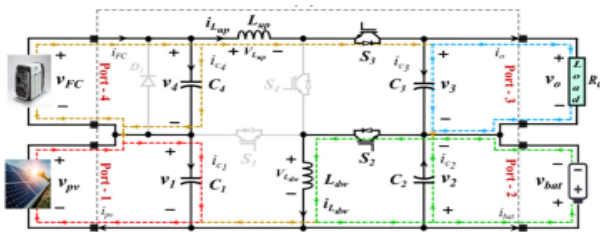


Fig.2.Switch S1 & S4 ON

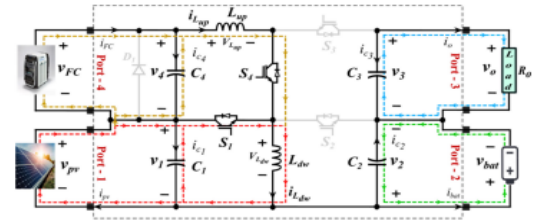


Fig.3.Switch S1 & S3 ON

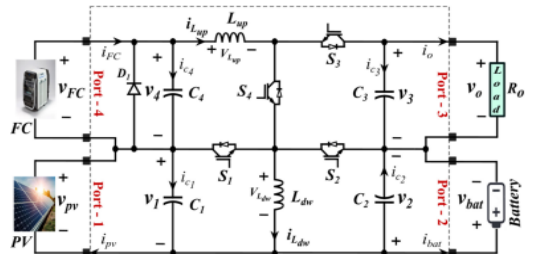


Fig.4.Switch S2 & S3 ON

IV.DESIGN OF SOLAR ARRAY AND CONVERTOR

The solar PV array for this system is built from four 200 W–220 W panels arranged in a 2-series, 2-parallel configuration. Each panel delivers around 30.12 V at its maximum power point, so two of them in series bring the array up to roughly 60 V, the voltage fed into the three-port DC-DC converter. A single panel's open-circuit voltage is about 36.06 V, which puts the open-circuit voltage of the full array at around 72 V. Running two such series strings in parallel raises the array's current rating and, with it, the available power. Together, this gives enough voltage and current for the multi-port converter to operate efficiently, with the array supplying about 60 V under normal conditions, exactly what the rest of the system is designed around.

$$V_{in} = N_s * V_m \dots \dots \dots \text{equation 4.1}$$

$$V_{in} = 2 * 30.12 \dots \dots \dots \text{equation 4.2}$$

$$V_{in} = 60.24 \text{ V} \dots \dots \dots \text{equation 4.3}$$

N_s = Number of PV modules in series

V_{mp} = Voltage at maximum power of one module

Converter behaves like Boost + Switched Capacitor Multiplier

The gain is approximately

$$V_{out} = \frac{(1+n)}{(1-D)} \times V_{in} \dots \text{equation 4.4}$$

D = Duty cycle

n = Switched capacitor multiplier stage

V_{in} = PV voltage

V_{in}=60V

Duty cycle D=0.7

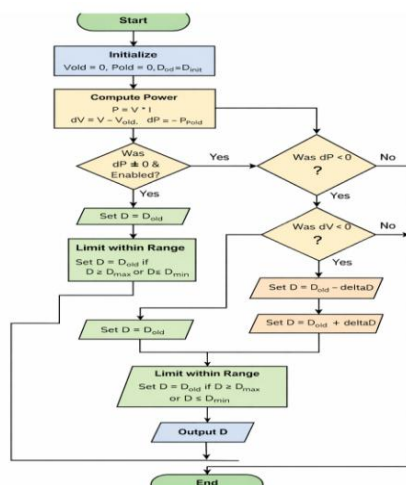
Multiplier stage n=2

$$V_{out} = \frac{(1+2)}{(1-0.7)} \times 60$$

$$= \frac{3}{0.3} \times 60$$

= 600V

Fig.5. Flowchart of MPPT controller based on the Perturb & Observe algorithm



V. DESIGN OF INDUCTOR & CAPACITOR

In the multi-port boost converter, the inductor stores energy while the switch is ON and releases it once the switch turns OFF, which keeps current flowing continuously and keeps ripple down. Choosing the right inductor value has a direct bearing on efficiency, ripple current, and how quickly the converter responds to changes, so it is calculated from the standard boost-converter design relation

equation:

$$L = \frac{(V_{in} \times D)}{f_s \times \Delta I_L} \dots \text{equation 4.5}$$

Where:

L = Inductor value

V_{in} = Input voltage

D = Duty cycle

f_s = Switching frequency

ΔI_L = Inductor ripple current

Inductor Value Calculation

V_{in}=60V

Duty cycle:

D=0.7

Switching frequency:

f_s=20kHz

Ripple current (20% of input current assumed):

ΔI_L=2A

$$L = \frac{60 \times 0.7}{2000 \times 2} = 1.05 \text{mH}$$

In this switched-capacitor-based high-gain converter, however, ripple current is already reduced thanks to:

Two inductors, Multiple capacitors

So smaller inductance is sufficient

Final selected value:

L=0.2mH

The output capacitor's job is to hold the DC output steady by absorbing voltage ripple; it also sharpens the converter's transient response and adds to its overall stability. Its value follows from the equation below.

$$C = \frac{(I_{out} \times D)}{(f_s \times \Delta V)} \dots \text{equation 4.6}$$

$$I_o=5A$$

$$D=0.7$$

$$f_s=20kHz$$

$$\Delta V_o=5V$$

$$C = \frac{5 \cdot 0.7}{2000 \cdot 5} = \frac{3.5}{100000}$$

$$C = 35 \mu F$$

In high gain converter: To reduce:

Voltage ripple Switching spikes

Output instability $35 \mu F \rightarrow$ High ripple
 $1200 \mu F \rightarrow$ Very low ripple

$$C=1200\mu F$$

VI. SIMULATION RESULTS & DISCUSSION

The system performance is evaluated by considering the variations of the input voltage, the regulation of the output voltage, the shape of the inductor current waveform, the stability of the capacitor voltage and the power sharing between the sources. To check the proper tracking of the P&O MPPT technique, the PV system was run at different levels of solar irradiance and the fuel cell and the battery were tested alone to make sure that they can supply the energy when the solar generation decreases. In the simulation, the multi-port converter boosts the 48-60 V input to around 500 V DC with low ripple and good efficiency. The controller manages the DC-link voltage regulation and shares the power smoothly between the PV, fuel cell and battery. The inverter output was also checked for clean DC-AC conversion and steady AC waveform. These results together point to reliable operation, large voltage gain, reduced switching stress and good utilization of the renewable sources.

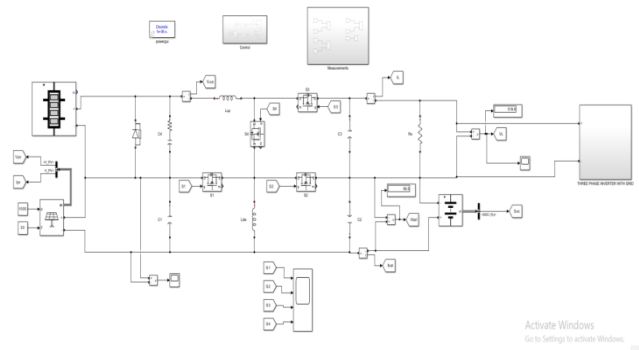


Fig.6.Simulation block diagram of PV,Fuelcell,battery Integration

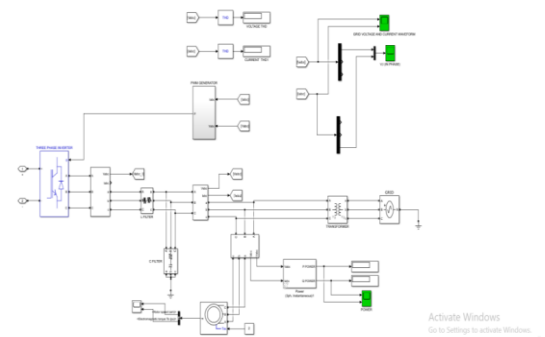


Fig.7.Simulation block diagram of grid synchronisation & three phase induction motor connection

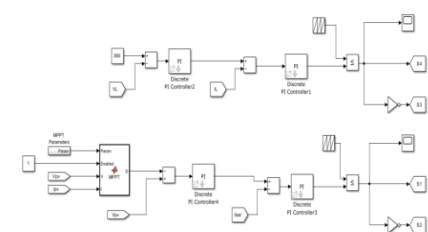


Fig.8. Simulation block diagram of PI controller

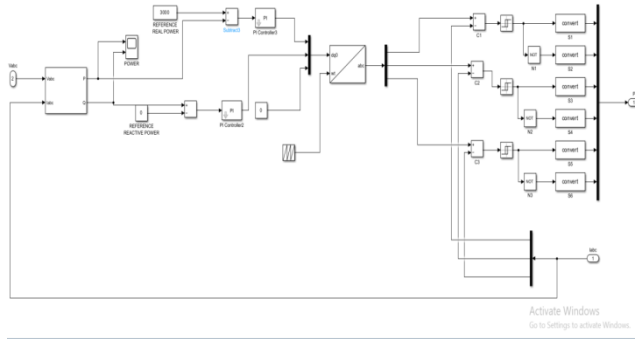


Fig.9. Simulation block PWM Pulse generation

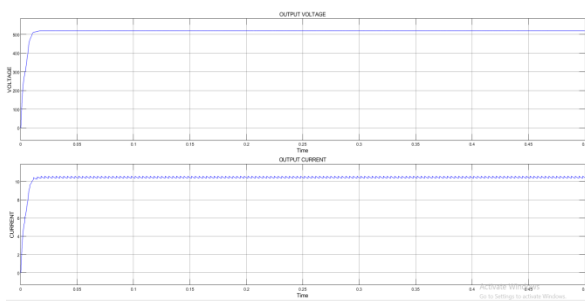


Fig. 10. Simulation of output voltage & current from multiport convertor

The figure shows the output voltage and current waveforms of the high-gain converter. Starting from zero, the output voltage climbs steadily and settles at around 520 V within about 0.02 seconds, a fast response that points to stable converter operation. Once it settles, the voltage stays essentially flat with negligible ripple, a good indication that the 1200 μF output capacitor is doing its job. Overall, these waveforms confirm that the converter steps the 60.24 V input up to a stable 520 V output, with voltage and current characteristics that suit a grid-connected inverter application

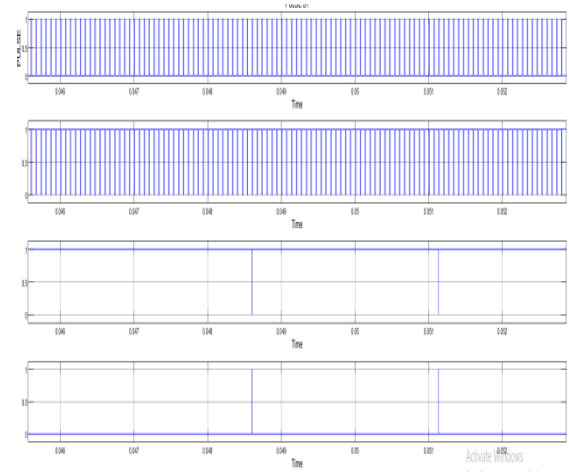


Fig.11. Simulation of battery voltage &SoC(%) VectorControl

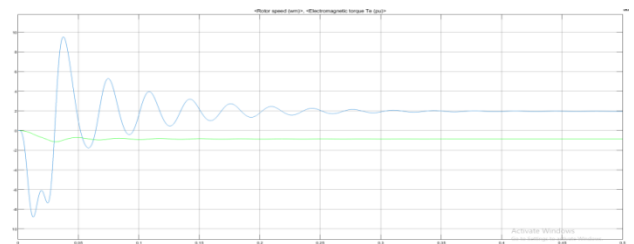


Fig.12.Simulation of Pulse applied to S1,S2,S3,S4

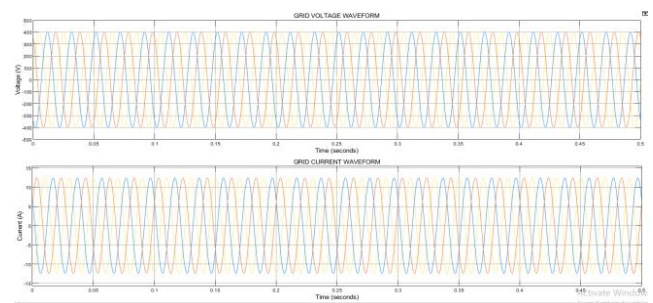


Fig.13. Output voltage and current waveform applied to Grid

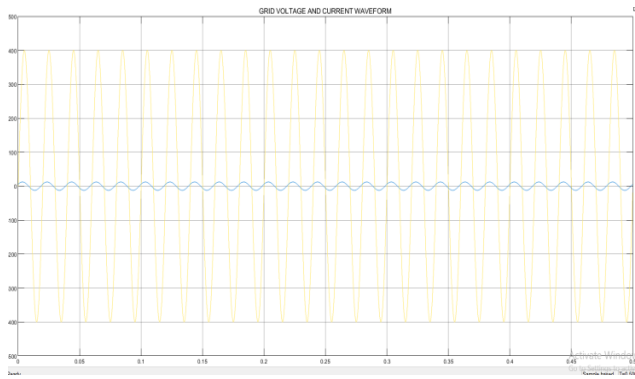


Fig.14.voltage and current in Phase before grid synchronisation

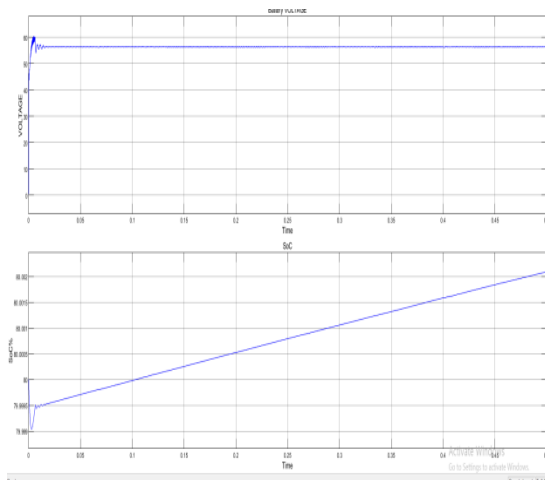


Fig.15. Output Real and Reactive power from Inverter

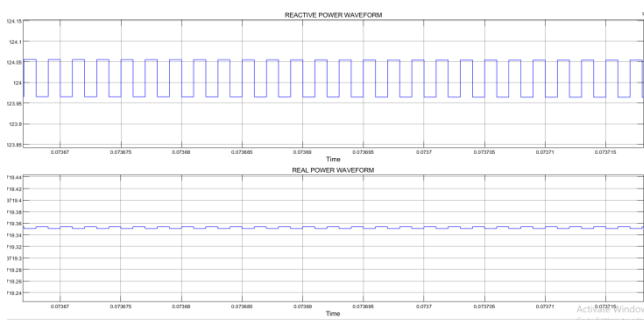


Fig.16. Torque & speed Characteristics of Three phase induction motor

These waveforms represent the steady state operation of the multiport converter after it is connected to the grid via the inverter stage. The grid voltage is a clean sinusoid, peaking at around 400 V which is consistent with standard AC grid conditions. The grid current

closely follows it in phase, which is a sign that the system runs near unity power factor and delivers mostly real power with very little reactive exchange. The reactive power itself is close to zero, only small high frequency ripples are present due to the switching action of the power devices and the finite resolution of the controller. These are minor and do not alter the overall picture. They confirm that the control strategy is holding the reactive power near zero as intended. Meanwhile real power is settled down at about 719 W with small amount of ripple, confirming that the converter delivers a fairly constant amount of active power to the grid. Again the small oscillations here are typical of PWM based converters and are mainly due to switching and filtering effects rather than any control fault. The overall results indicate the multiport converter and inverter stage cooperate to regulate the power flow, maintain synchronization with the grid, and transfer energy efficiently with good power quality. The lower traces in the figure are gating signals for the other switches of the converter. They switch less often than the main PWM signals, as they mainly handle mode selection, and the transfer of energy between ports, e.g. switching between source-to-load (bottom trace), and storage-to-load (top trace) operation. The short, clean transitions between high and low states show that switching is well controlled with no overlap between switches in the same leg and no risk of a short circuit. To summarize, high-frequency PWM signals control voltage and current regulation, and slower gating signals coordinate power sharing among multiple ports of the converter.

VII.CONCLUSION

The objective of this work is to design and analyze a multi-port DC-DC converter for integrating multiple energy sources such as photovoltaic (PV) array, battery and fuel cell and to provide a high step-up output voltage. The converter so produced can accept low input voltage (about 60 V from the PV array) and step it up to a much higher voltage (about 600 V), which makes it suitable for applications such as electric vehicles and DC microgrids.

- The design has some notable advantages compared to the conventional boost converter: Increased voltage gain with moderate duty cycles
Lower switching stress on power devices
- Efficient power sharing between multiple sources
- Flexible operation under different modes (PV only, battery only, hybrid mode)

The simulation results back up stable operation across a range of conditions, including changes in load and in which sources are available, and the chosen inductor and capacitor values keep the current and voltage waveforms smooth with minimal ripple.

Overall, this converter improves system reliability, efficiency, and adaptability, making it a promising building block for renewable energy integration.

IX. REFERENCE

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